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Earthquake-triggered increase in biospheric carbon export from a mountain belt

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ABSTRACT

On geological time scales, the erosion of carbon from the terrestrial biosphere and its burial in sediments can counter CO_2 emissions from the solid Earth. Earthquakes may increase the erosion of this biospheric carbon and supply it to mountain rivers by triggering thousands of landslides which rapidly strip hillslopes of vegetation and soil. At the same time, elevated river sediment loads may promote more efficient carbon burial over the long term. However, riverine export of earthquake-mobilized carbon has remained poorly constrained. Here we quantify biospheric carbon discharge by the Zagunao River following a large earthquake, with a unique set of samples collected before and after the A.D. 2008 M_w 7.9 Wenchuan (China) earthquake. Radioactive and stable carbon isotopes are used to isolate the biospheric carbon, accounting for rock-derived organic carbon inputs. Riverine biospheric carbon discharge doubled in the downstream reaches, with moderate landslide impact, following the earthquake. The rapid export of carbon from earthquake-triggered landslides appears to outpace its degradation on hillslopes while sediment loads are elevated. This means that enhanced river discharge of biospheric carbon following large earthquakes can link active tectonics to CO_2 drawdown.

INTRODUCTION

Physical erosion drives the export of carbon from the terrestrial biosphere and its delivery to rivers (Berhe et al., 2007; Hilton et al., 2008; Galy et al., 2015). The resulting biospheric particulate organic carbon ($POC_{biosphere}$) flux carried by rivers is globally important, with an estimated 157 (+74)/(–50) megatons of carbon per year (MtC yr^{-1}) delivered to the oceans (Galy et al., 2015). Association of this $POC_{biosphere}$ with inorganic sediment can increase its likelihood of long-term burial (Galy et al., 2007; Blair and Aller, 2012; Kao et al., 2014). The erosion of $POC_{biosphere}$ therefore contributes to the drawdown of atmospheric CO_2 over geological timescales, countering CO_2 emissions from volcanism, metamorphism and oxidation of organic matter in sedimentary rocks

(Berner, 1982; France-Lanord and Derry, 1997). It follows that the tectonic and climatic factors which control erosion (Dadson et al., 2003) may also control $POC_{biosphere}$ transfer and CO_2 drawdown (Galy et al., 2015; Hilton, 2016). Large earthquakes may directly link carbon transfer by erosion to active tectonics (St-Onge and Hillaire-Marcel, 2001) by triggering tens of thousands of landslides (Malamud et al., 2004; Li et al., 2014). These landslides deliver sediment to river channels, increasing sediment discharge over decades to centuries (Hovius et al., 2011; Wang et al., 2015) and contributing importantly to long-term erosion (St-Onge and Hillaire-Marcel, 2001; Malamud et al., 2004; Howarth et al., 2012). At the same time, landslides can erode forest biomass and soil, harvesting $POC_{biosphere}$ recently fixed from atmospheric CO_2 (Garwood et al., 1979; Hilton et al., 2011).

Previous studies have assumed that $POC_{biosphere}$ stripped from hillslopes by earthquake-triggered landslides is a CO_2 source due to oxidation in the landscape (Garwood et al., 1979; Chen et al., 2009). However, this is at odds with observations that mountain rivers can rapidly erode and export landslide-mobilized POC (Hilton et al., 2008; Kao et al., 2014). Preservation of some of this eroded $POC_{biosphere}$ in sedimentary deposits could instead store carbon (Berhe et al., 2007; Kao et al., 2014; Galy et al., 2015). Landslides triggered by the A.D. 2008 M_w 7.9 Wenchuan (China) earthquake were estimated to have mobilized ~14 MtC (Chen et al., 2009), ~10% of the global annual $POC_{biosphere}$ discharge by rivers (Galy et al., 2015). Despite this recognition, the erosion of landslide-mobilized $POC_{biosphere}$ following large earthquakes remains unconstrained, mainly because of lack of relevant data before and after such events.

Here we assess the erosion of $POC_{biosphere}$ following the Wenchuan earthquake, which triggered >57,150 landslides covering a total area of >396 km^2 (Li et al., 2014) and caused suspended-sediment discharge to increase by up to 7 times in the 5 yr following the earthquake (Wang et al., 2015). We address the daily to multi-annual impacts on river $POC_{biosphere}$ discharge, using suspended load samples (Tables DR1 and DR2 in the GSA Data Repository[1]) collected before (1 April 2005 to 10 May 2008) and after (13 May 2008 to 10 August 2010) the earthquake from the Zagunao River, a major tributary of the Min Jiang (Fig. DR1 in the Data Repository). We model the erosion of $POC_{biosphere}$ over decades, accounting for both its river export and degradation.

STUDY AREA, MATERIALS AND METHODS

The Wenchuan earthquake triggered landslides covering 12.5 km^2 within the Zagunao catchment above the Sangping gauge (Li et al., 2014; Wang et al., 2015), 0.27% of the total contributing area (4629 km^2). Suspended-sediment discharge more than doubled in response to the landslide inputs after the earthquake (Wang et al., 2015). Suspended load samples were collected both upstream at the Zagunao gauge (contributing area 2404 km^2) and downstream at the Sangping gauge (Fig. DR1). To quantify $POC_{biosphere}$ discharge, we accounted for the input of rock-derived or 'petrogenic' POC (POC_{petro}), since its erosion and reburial does not impact contemporary atmospheric CO_2 (Galy et al., 2007; Hilton et al., 2008). To do this, 154 suspended load samples were analyzed for total organic carbon content ($[OC_{total}]$) (Table DR1). 2 river bed and 33 suspended load samples spanning a wide range in $[OC_{total}]$ and water discharge (Q_w) values were selected for analysis of stable C isotope composition ($\delta^{13}C_{org}$, ‰) and radiocarbon (^{14}C) activity, reported as 'fraction modern' (F_{mod}) (Table DR2).

[OC_{total}] and $\delta^{13}C_{org}$ were determined by a Costech CHN elemental analyzer (EA), coupled by continuous flow via CONFLO-III to a Thermo-Delta-V isotope ratio mass spectrometer at Durham University (UK), normalized to standards and corrected for internal blanks. F_{mod} of POC samples was measured by accelerator mass spectrometry after carbonate removal and graphitization at the University of California, Irvine, USA. Sample preparation background was subtracted based on measurements of ^{14}C-free coal. [OC_{total}], $\delta^{13}C_{org}$ and F_{mod} values of suspended sediment samples were corrected for the full filtration procedural blank (see details in the Data Repository).

IMMEDIATE RESPONSE OF POC TO THE WENCHUAN EARTHQUAKE

Over the sampling periods, the F_{mod} values of the Zagunao River suspended sediment range from 0.27 to 0.94 and are significantly negatively correlated with $\delta^{13}C_{org}$ values ($P < 0.01$), which vary from –25.7‰ to –19.3‰ (Fig. 1A). Grain size separates of suspended load also follow this trend (Fig. DR2), with material >250 µm containing visible woody fragments having the highest F_{mod} values. River bed materials have lower F_{mod} values ($F_{mod} < 0.08$) and higher $\delta^{13}C_{org}$ values than suspended load (Fig. 1A). These patterns can be explained as the result of mixing ^{14}C-depleted POC_{petro} with ^{14}C-enriched $POC_{biosphere}$ during erosion and fluvial transport, consistent with observations from mountain rivers around the world (Hilton et al., 2008; Galy et al., 2007, 2015; Kao et al., 2014).

Erosional processes which mobilize clastic sediment and POC_{petro} mix them with $POC_{biosphere}$ from soils and vegetation (Hilton et al., 2008, 2011). Interestingly, we find no significant difference in the $\delta^{13}C_{org}$ and F_{mod} of total POC (POC_{total}) before and after the earthquake (Fig. 1A; $P > 0.4$), suggesting similar relative contributions of $POC_{biosphere}$ and

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POC_{petro} to the fine suspended load (Fig. 1A). Although landslide depths extended below soil layers (West et al., 2014) and are thus expected to contain a higher proportion of POC_{petro}, our results suggest that the fine-grained component of landslide material that contributed to suspended sediments in the years immediately after the earthquake was similar to pre-earthquake soils. To quantify the amount of biospheric carbon in our samples, we use an end-member mixing analysis (Galy et al., 2015; Kao et al., 2014) to calculate the POC_{petro} content ($[OC_{petro}]$) and, by subtraction from $[OC_{total}]$, the $POC_{biosphere}$ content ($[OC_{biosphere}]$) (See the GSA Data Repository for methods).

Immediately following the earthquake, $POC_{biosphere}$ concentration increased 8 times (0.81–6.52 mgC L^{-1}) from 10 May to 15 May 2008, whereas Q_w was relatively constant at the Sangping gauge (Fig. 2A). This suggests immediate input of $POC_{biosphere}$ to the river from earthquake-triggered landslides, similar to the increase in suspended sediment concentration (SSC) over this time (Wang et al., 2015). Over the following 10 days, both $POC_{biosphere}$ and POC_{total} decreased (Fig. 2A). Thus, while Q_w remained constant in the days following the earthquake, erosion processes acted to gradually remove $POC_{biosphere}$ and fine clastic sediment that was immediately available for transport.

ENHANCED $POC_{biosphere}$ DISCHARGE FOLLOWING THE EARTHQUAKE

To determine the monthly to annual discharge of $POC_{biosphere}$, we first examine the relationship between SSC (for which we have daily data) and POC_{total} content (SSC × $[OC_{total}]$, mgC L^{-1}). The relatively constant weight % of POC during the study period suggests that the POC_{total} concentration is positively correlated with SSC at both gauging stations (Fig. 1B). We use this relationship to calculate POC_{total} concentrations at times when we have hydrological measurements (2006–2011) but no geochemical measurements. The [OC_{petro}] of suspended sediments is estimated from the end-member mixing analysis (Fig. DR3) to then quantify daily POC_{petro} discharge. Daily $POC_{biosphere}$ discharge is calculated by difference from the POC_{total} and POC_{petro} discharge, following methods applied in a recent global compilation (Galy et al., 2015).

The average annual $POC_{biosphere}$ discharge at the Sangping station was 4586 ± 1756 tC yr^{-1} before the earthquake (2006 and 2007) and 5696 ± 2645 tC yr^{-1} after the earthquake until the end of 2011 (Table DR3). At the same time, POC_{petro} discharge was 2722 ± 1030 tC yr^{-1} before and 3359 ± 1506 tC yr^{-1} after. Thus the magnitude of $POC_{biosphere}$ and POC_{petro} fluxes did not change within uncertainty. Any change associated with the earthquake may be obscured by the influence of discharge on annual-timescale $POC_{biosphere}$ fluxes (Hilton, 2016). Over the study period, high $POC_{biosphere}$ discharge was associated with high frequency of intense runoff events (Fig. DR4 and Table DR3). More of these events occurred prior to the earthquake, complicating the direct comparison of pre- and post-earthquake fluxes.

In order to normalize for these effects and to isolate the impact of the earthquake, we assume that the proximity of the two nested gauging stations means that they experience similar changes in runoff (Fig. DR1). We then quantify downstream $POC_{biosphere}$ gain as the ratio of downstream to upstream $POC_{biosphere}$ discharge. Net $POC_{biosphere}$ deposition (and/or $POC_{biosphere}$ degradation) between the gauging stations would result in a downstream $POC_{biosphere}$ gain of <1, whereas erosion of soil and vegetation from hillslopes between the stations would result in a downstream $POC_{biosphere}$ gain of >1. Summing fluxes over half years to average over short-term variability, downstream $POC_{biosphere}$ gain before the earthquake (2006 and 2007) varies between 1.0 ± 0.2 and 1.7 ± 0.2 (Fig. 2B). In the first half year of 2008, downstream $POC_{biosphere}$ gain increases to 4.7 ± 0.2. From the earthquake until the end of 2011, the average gain is 2.8 ± 0.9 (Fig. 2B), significantly higher than that before the earthquake.

This 1.4–4.0× increase of downstream $POC_{biosphere}$ gain can be explained by the increased erosion and supply of $POC_{biosphere}$ to river channels from earthquake landslides, which impacted 7.2 km^2 of the catchment between the gauging stations (Li et al., 2014; Wang et al., 2015). This increase in $POC_{biosphere}$ supply is not observed in the calculated fluxes at each station because of the competing effect of less frequent intense runoff after the earthquake (Fig. DR4). $POC_{biosphere}$ fluxes actually decreased after the earthquake at the upstream station, where landslide area was smaller (5.3 km^2 total) than at the downstream station and where transport capacity may be reduced due to lower Q_w. Given the hydrological controls on POC fluxes (Hilton, 2016), we focus on the downstream $POC_{biosphere}$ gain as an indicator of the earthquake effect. The increase in downstream $POC_{biosphere}$ input observed immediately following the earthquake (Fig. 2A) is sustained over the three years which followed (Fig. 2B). The lack of a declining trend in downstream $POC_{biosphere}$ gain following the earthquake (Fig. 2B) suggests that export of $POC_{biosphere}$ mobilized by the earthquake may have been limited by available runoff across this reach.

RIVER EXPORT OUTPACES DEGRADATION OF THE EARTHQUAKE-MOBILIZED $POC_{biosphere}$

The sediment samples from the Zagunao River demonstrate for the first time that earthquake-mobilized $POC_{biosphere}$ can be rapidly delivered (Fig. 2A) and discharged by rivers over several years (Fig. 2B), rather than being oxidized rapidly in the landscape (cf. Garwood et al., 1979; Chen et al., 2009). Over decadal timescales, $POC_{biosphere}$ may be stored in landslide deposits and landscape hollows (Berhe and Kleber, 2013) and represent a transient carbon sink (Hilton et al., 2011). Here we assess the erosion of this material and the consequences for the longer-term carbon cycle; we model the competing geomorphic and biochemical processes (see the Data Repository for methods) which may act on organic matter in river catchments (Stallard, 1998; Berhe et al., 2007; Blair and Aller, 2012). The model assumes (1) one-time input of eroded $POC_{biosphere}$ by earthquake-triggered landslides; (2) transport-limited export of $POC_{biosphere}$ by a mountain river; and (3) degradation by heterotrophic respiration of $POC_{biosphere}$ remaining in the landscape, using a single-pool model of organic degradation (Stallard, 1998; Trumbore, 2000; Blair and Aller, 2012). The key variables are the $POC_{biosphere}$ export rate (tC yr^{-1}) and the degradation rate (k, % yr^{-1}). Here, we make assumptions about these variables and their behavior to provide an upper estimate of the degradation losses.

Firstly we estimate the input of $POC_{biosphere}$ by landslides which occurred between the nested gauging stations on the Zagunao River (Fig. DR1), at 215,000 ± 14,000 tC of $POC_{biosphere}$ from vegetation and soil (see the Data Repository for methods). The post-earthquake $POC_{biosphere}$ discharge from this fluvial reach (difference between upstream and downstream stations) was 3487 ± 1599 tC yr^{-1} versus 948 ± 369 tC yr^{-1} before the earthquake. Assuming no degradation in the landscape (k = 0% yr^{-1}), it would take 85 ± 55 yr to remove all of the earthquake-mobilized $POC_{biosphere}$ at the present river $POC_{biosphere}$ discharge. Degradation reduces the amount of $POC_{biosphere}$ which is available for riverine export and potential longer-term sequestration (Fig. 3; Berhe et al., 2007). A single-pool model may overestimate degradation because it does not consider more persistent organic matter phases which may degrade at a slower rate (Trumbore, 2000; Blair and Aller, 2012). However, even at a high degradation rate indicative of a tropical soil with an organic-matter turnover time of ~50 yr (k = 2% yr^{-1}), our model predicts that ~60% of the $POC_{biosphere}$ mobilized by earthquake landslides escapes oxidation (Fig. 3). The modeled proportion of $POC_{biosphere}$ which is exported increases as k decreases; with k = 0.5% yr^{-1}, 83% of the earthquake mobilized $POC_{biosphere}$ is exported by rivers rather than oxidized. Thus, over decadal timescales, the model suggests that $POC_{biosphere}$ discharge by rivers is fast enough to export the majority of carbon (>60%) before it has the chance to be oxidized in the landscape (Fig. 3), supporting carbon discharge estimates from other fluvial systems with high erosion rates (Berhe et al., 2007). The impacts of tectonic events such as earthquakes are poorly represented in estimates of carbon flux by erosion (Galy et al., 2015), and our data suggest that these omissions lead to an underestimation of the global $POC_{biosphere}$ discharge by mountain rivers.

IMPLICATIONS

In terms of net CO_2 flux following the earthquake, it is first important to consider the fate of POC_{petro}. Erosion is a primary control on the rate of POC_{petro} oxidation and release of CO_2 (Hilton et al., 2014). This process is poorly quantified, although data from mountain rivers in Taiwan suggest that <20% of the total POC_{petro} flux (physical plus chemical denudation) is by oxidative weathering in high erosion rate settings (Hilton et al., 2014), with the rest exported as unoxidized POC_{petro}. Based on these estimates, post-earthquake CO_2 release by POC_{petro} oxidation in the Zagunao may be ~20% of the exported $POC_{biosphere}$ discharge, and so will not negate the CO_2 sink. Future work should seek to better quantify POC_{petro} oxidation rates and consider the role of extreme events.

Over geological time scales, $POC_{biosphere}$ discharged by rivers can contribute to CO_2 drawdown if it is buried in long-lived sedimentary deposits (Berner, 1982; Blair and Aller, 2012; Kao et al., 2014). While we cannot directly assess the burial of $POC_{biosphere}$ in this case, we note that the earthquake caused a large increase in suspended-sediment discharge from the Longmen Shan (Wang et al., 2015). In a variety of environments, the burial efficiency of organic matter is strongly linked to rates of sediment accumulation (Berner, 1982; Galy et al., 2007; Blair and Aller, 2012; Kao et al., 2014). The enhanced $POC_{biosphere}$ discharge following a large earthquake (Fig. 2) may thus be prone to efficient sedimentary burial. Qualitative observations of enhanced burial of terrestrial POC in lake sediments in the decades after multiple large earthquakes in the Southern Alps, New Zealand (Howarth et al., 2012) indicate that earthquakes are likely to be important for carbon transfer from mountain belts over longer timescales. The enhanced erosion and river discharge of biospheric carbon acts along with the potential for large earthquakes to increase CO_2 consumption via silicate-derived alkalinity (Jin et al., 2016). Together, these processes link active tectonics to CO_2 drawdown, providing a mechanism which links mountain building, erosion, and weathering to the global carbon cycle (Raymo and Ruddiman, 1992; France-Lanord and Derry, 1997).

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FIGURE CAPTIONS

Figure 1. Particulate organic carbon (POC) in the Zagunao River before and after the A.D. 2008 M_w 7.9 Wenchuan (China) earthquake. A: ^{14}C activity of POC (F_{mod}) versus stable carbon isotopic composition ($\delta^{13}C_{org}$) for the Zagunao (red circles) and Sangping (blue circles) gauges, before (open circles) and after (filled circles) the earthquake. The grey rectangles show the composition of the biospheric POC (upper left) and rock-

derived petrogenic POC (lower right) end-members. B: Relationships between suspended-sediment concentration (SSC) and total POC concentration, with symbols as per panel A. The red and blue lines are power-law fits through samples collected at the Zagunao (ZG) and at the Sangping (SP) stations, respectively. Analytical errors are smaller than the point sizes.

Figure 2. The impact of the A.D. 2008 Wenchuan (China) earthquake on particulate organic carbon (POC) transfer in the Zagunao River. A: $POC_{biosphere}$ concentration (circles) and water discharge (Q_w) during May 2008 at Sangping station, normalized to the 2006-2011 average (Q_w/Q_{mean}) (gray line), showing an immediate increase in $POC_{biosphere}$ concentrations following the earthquake. B: Discharge of $POC_{biosphere}$ quantified as 6 monthly averaged downstream $POC_{biosphere}$ gain (the ratio of downstream to upstream $POC_{biosphere}$ flux from two nested gauging stations on the Zagunao River; Fig. DR1 [see footnote 1]). Whiskers indicate propagated errors, and horizontal lines show the average downstream $POC_{biosphere}$ gain ($\pm\sigma$) values before and after the earthquake.

Figure 3. Modeled time evolution of earthquake-mobilized $POC_{biosphere}$ residing in the Zagunao River catchment. Open circles show the decrease in the amount of earthquake-mobilized $POC_{biosphere}$ remaining in the landscape, using the post-earthquake riverine $POC_{biosphere}$ discharge from the downstream reaches. The black, red, and orange lines are the modeled time evolution of earthquake-mobilized $POC_{biosphere}$ remaining in the landscape (See the Data Repository [see footnote 1] for methods), and a $POC_{biosphere}$

degradation rate *k* (% yr^{-1}). The green numbers show the percentage of $POC_{biosphere}$ exported by the river, and blue numbers show the percentage oxidized to CO_2.

[1]GSA Data Repository item 2016xxx, Figures DR1–DR5, Tables DR1–DR4, and supplementary methods, is available online at www.geosociety.org/pubs/ft2016.htm, or on request from diting@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

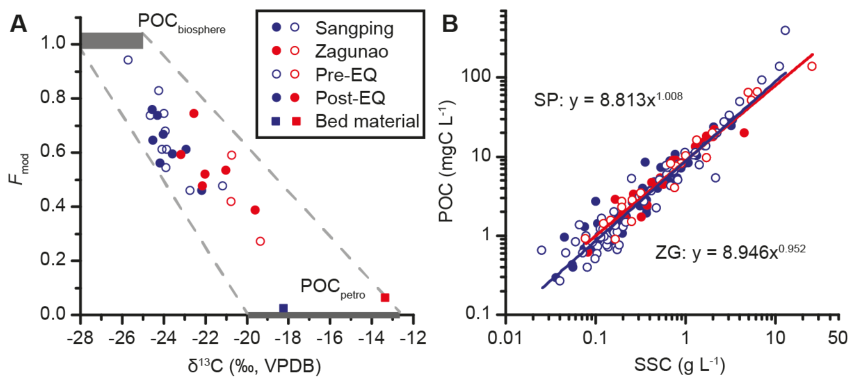

Figure 1

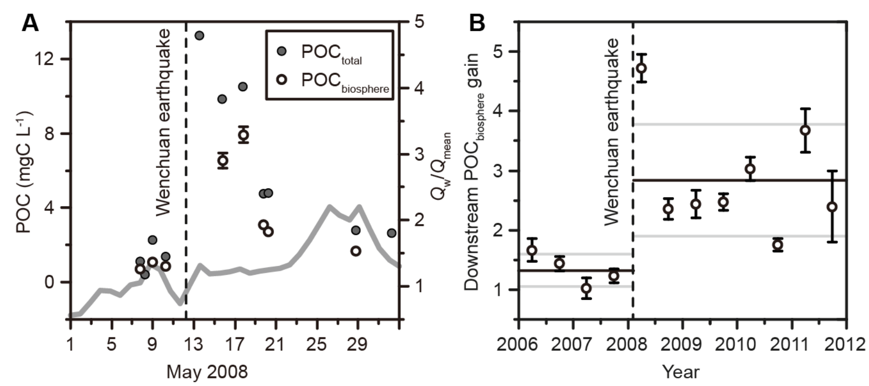

Figure 2

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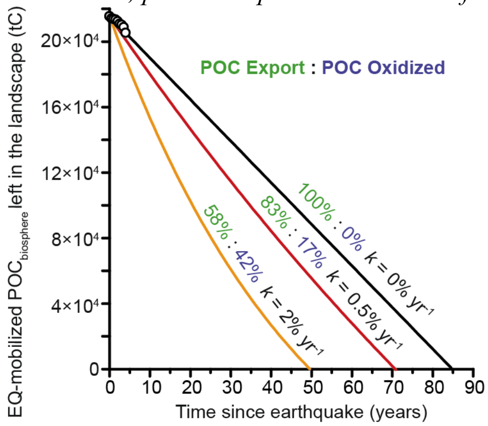

Figure 3